Hyperspectral Remote Sensing of the Coastal Ocean: Adaptive Sampling and Forecasting of Nearshore *In Situ* Optical Properties

Mark A. Moline
Biological Sciences Department
California Polytechnic State Universtiy
San Luis Obispo, CA 93407
phone: (805) 756-2948 fax: (805) 756-1419 email: mmoline@calpoly.edu

Award #: N00014-99-1-0197
http://marine.rutgers.edu/cool/hycode2/hycode2.html

LONG-TERM GOALS

We are developing and validating an integrated rapid environmental assessment capability that will be used to feed a developing nowcast/forecast system. The focus of the rapid environmental assessment is characterizing the 3-dimensional evolution of inherent optical properties (IOPs) in nearshore coastal waters. This is being accomplished by developing an integrated observation network providing real-time data allowing for adaptive sampling in nearshore coastal waters. The data will also be used to develop hyperspectral remote sensing techniques for optically complex coastal waters while also providing physical/optical data for coupled data assimilative hydrodynamic ecosystem models currently under development. This will support the development and validation infrastructure for the Navy Earth Map Observer (NEMO) satellite system.

OBJECTIVES

I propose to make biological/chemical/optical measurements that supplement the data collected by the existing observation network in the coastal waters off the coast of New Jersey. Obtaining a suite of fine-scale physical, chemical and biological measurements will significantly advance our understanding of the processes governing the temporal and spatial variability of in water IOPs in the coastal ocean. This, combined with the forecasting objectives of the observational network, will also provide a mechanism and framework for predicting these dynamics in the coastal ocean. In working with other principal investigators, the specific objectives of this project are:

To develop and deploy moored, shipboard, and autonomous bio-optical systems in the coastal ocean to ground-truth remote sensing imagery.

To use rapid environmental assessment techniques to quantify the physical, chemical and biological processes that define the spatial and temporal variability in the spectral IOPs for the nearshore coastal ocean during summer-time upwelling

To refine and calibrate existing hyperspectral optical models to derive IOPs from remotely sensed data using the above datasets.

To collaborate with other principal investigators to couple a radiative transfer ecosystem module to the data-assimilative hydrodynamic model.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Hyperspectral Remote Sensing of the Coastal Ocean: Adaptive Sampling and Forecasting of Nearshore In Situ Optical Properties**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Biological Sciences Department,,California Polytechnic State Universtiy,,San Luis Obispo,,CA, 93407**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We are developing and validating an integrated rapid environmental assessment capability that will be used to feed a developing nowcast/forecast system. The focus of the rapid environmental assessment is characterizing the 3-dimensional evolution of inherent optical properties (IOPs) in nearshore coastal waters. This is being accomplished by developing an integrated observation network providing real-time data allowing for adaptive sampling in nearshore coastal waters. The data will also be used to develop hyperspectral remote sensing techniques for optically complex coastal waters while also providing physical/optical data for coupled data assimilative hydrodynamic ecosystem models currently under development. This will support the development and validation infrastructure for the Navy Earth Map Observer (NEMO) satellite system.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

APPROACH

We have been conducting a series of Coastal Predictive Skill Experiments (CPSE) each summer at the Long-term Ecosystem Observatory (LEO-15) offshore Tuckerton, NJ. Model and observation network improvements tested each winter with existing data are used in an operational setting the following summer. The above scenario closely resembles the current paradigm for Rapid Environmental Assessment in preparation for an approaching crisis. Well before the crisis, the climatology is the most useful (and may be the only) environmental product for mission planning. As the crisis approaches, the usefulness of climatology rapidly degrades, and accurate forecasts take over as the most desired environmental product. When the crisis is imminent, forecasts also begin to lose their value as operators depend more on real-time data products and nowcast analyses. Coordinated shipboard (physical and bio-optical) and multiple AUV adaptive sampling surveys of the upwelling centers were conducted based on the real-time observations and the model forecasts. The resulting environmental assessment capability is used then to adaptively characterize the spatial and temporal variability in the in-water inherent optical properties. This system is used to ground-truth hyperspectral imagery in support of the Navy Earth Map Observer (NEMO).

WORK COMPLETED

Table 1. Discrete samples taken as part of the HyCODE effort in 200 and 2001 and the level currently processed.

CalPoly Discrete Samples 2001-2000	2001		2000	
Sample Type	**Total Sample Collected**	Total Sample Processed	**Total Sample Collected**	Total Sample Processed
Colored Dissolved Organic Matter	95	95	105	105
Dissolved Organic Carbon	93	-	N/A	N/A
CHN	97	-	N/A	N/A
HPLC	250	-	176	176
Fluorescence	233	233	198	198
Absorption and Particulate Spectra (QFT)	234	-	146	146
Biological Oxygen Demand	78	78	34	34
DNA	19	-	N/A	N/A
PI curves	12	-	7	7
Phytoplankton Samples	35	-	30	-
Total Suspended Matter (LPC)	50	-	61	61

Over the course of the year, 757 discrete samples were processed at the field site and at Cal Poly State University (Table 1). Weekly planning relied on 8 dynamical forecasts generated through the Regional Ocean Model (ROMs) forecasts, which during the 2001 experiment successfully predicted alternating upwelling/downwelling events. The model forecasts were improved due to the coupling of ROMs to

the high-resolution COAMPs weather forecasts. These forecasts, real-time CODAR fields, and *in situ* data from the autonomonous nodes assisted in choosing flight missions for the aircraft (PHILLs-1, PHILLs-2, AVIRIS, Proteus, SPECTIR) and position three ships under the aircraft for *in situ* validation. The *in situ* nodes were outfitted to measure the inherent optical properties (absorption, scatter, attenuation, angular scattering, backscatter) and biology (fluorescence, bioluminescence, particle number and size). Ships were outfitted to measure the inherent optical properties (absorption, scattering, attenuation, backscatter), apparent optical properties (irradiance, radiance, reflectance, remote sensing reflectance), and biology (fluorescence, particle size and number, bioluminescence). The 29-day experiment consisted of four ships, five aircraft, data from the international constellation of ocean color satellites, a nested surface current radar network, flights of untended AUVs, and profiling of *in situ* nodes. In excess of 200 discrete samples for laboratory analyses were collected. The samples are being analyzed for filter pad absorption spectra, particle size, phytoplankton pigmentation, and nutrients (total samples equals 1,196; Table 1). A smaller proportion of these samples will be analyzed for suspended particulate matter, particulate carbon/nitrogen, dissolved oxygen, primary productivity and dissolved organic carbon. Field sampling was coordinated through the modeling/observation system and allowed for 1) 16 clean overflights providing hyperspectral ocean color data with complete remote sensing ground truth data from the research fleet, 2) 5 days with more then two aircraft flying at one time allowing for one of the first times vicarious calibration between aircraft systems, and 3) calibration of atmospheric parameters using NASA-funded aircraft.

RESULTS

We experienced upwelling and downwelling events in the summer of 2001. Topographic variations associated with ancient river deltas caused upwelled water to evolve into a recurrent upwelling center. Frequent wind reversals resulted in downwelling followed by subsequent upwelling. The net result was a sustained phytoplankton bloom extending over 40 km offshore. The bloom was characterized by two distinct zones of high chlorophyll in the nearshore (chlorophyll a > 5 mg m^{-3}) and offshore waters (> 1.5 mg m^{-3}) (see Report OP63). These onshore and offshore gradients are recurrent features as seen from the major absorbing constituents during the 2000 field effort (Figure 1). Associated with the high chlorophyll were optically turbid waters above the thermocline (a_{440} nm > 2.0 m^{-1}). Below the thermocline, the water was optically-clear (a_{440} nm < 1.0 m^{-1}). The bottom water temperatures were as low as 10 degrees Celsius, indicating cold pool water from the continental shelf. Indications were that sinking organic carbon from above the thermocline was leading to significant oxygen declines in the bottom waters. The surface flow field consisted of a cyclonic eddy within the cold upwelling center and a northward flowing surface jet on the warm side of the upwelling front that made a sharp anticyclonic turn around the cold center. Subsurface current observations indicated that the northward-flowing upwelling jet on the offshore side was confined to the upper water column above the thermocline, and as in past years a southward-flowing, subsurface jet was observed on the nearshore side below the thermocline. The optical features of the upwelled waters were dominated by particulate organic carbon (POC).

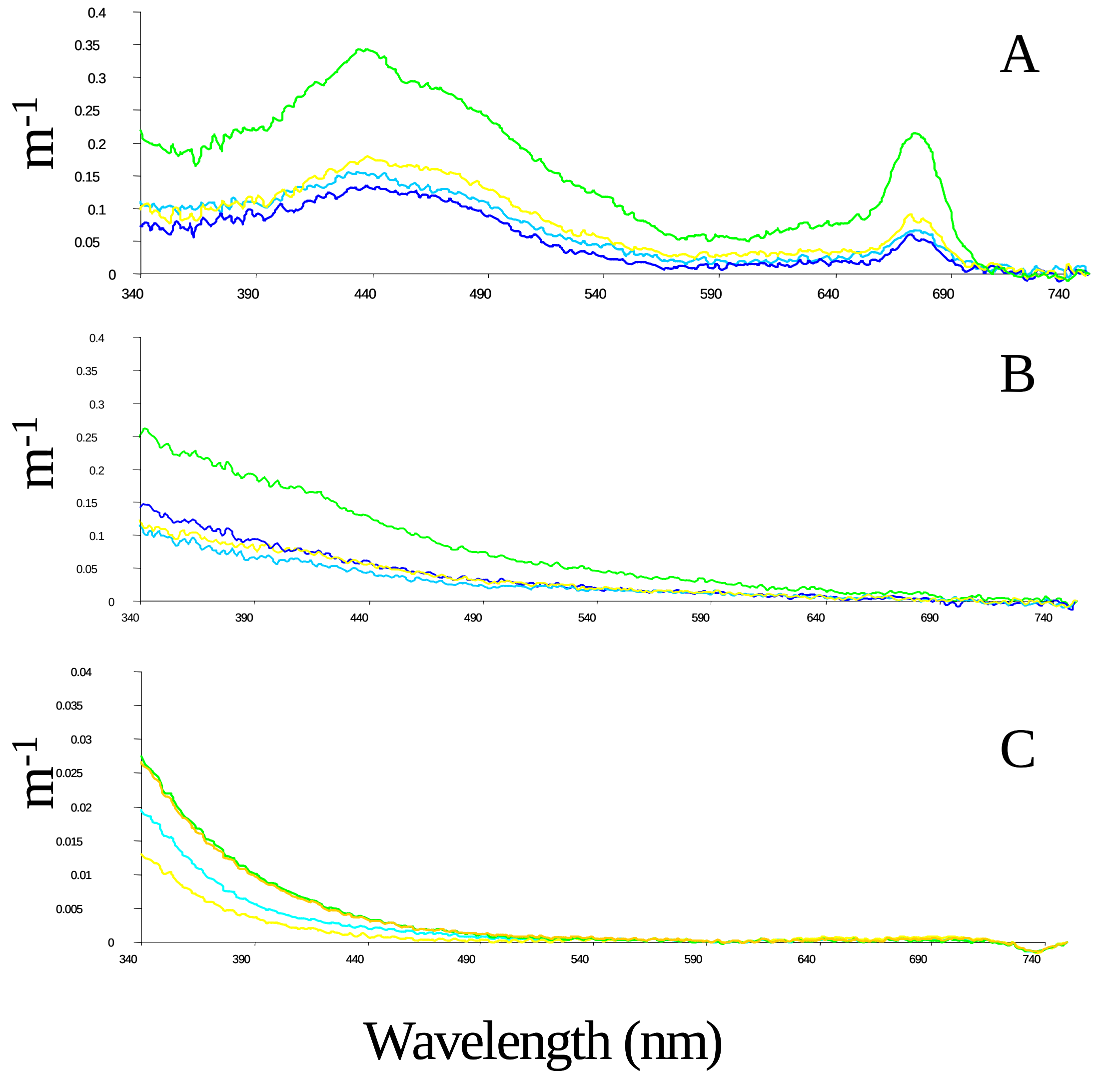

Figure 1. Absorption spectra for discrete samples collected July27th, 2000 of A) Phytoplankton, B) Particulate Matter and C) Colored Dissolved Organic Material (CDOM). Samples represent an on/offshore gradient from green to yellow to dark blue and light blue. Samples were evenly spaced across a transect of approximately 15 kms.

The bulk *in situ* absorption measurements could be inverted into the particulate and dissolved components as well as the dominant phytoplankton spectral class . Phycobilin-containing algae were problematic. In these waters a significant number of cryptophytes are present and the current IOP inversion models utilize spectral shapes more representative of low light adapted cyanobacterial picoplankton. This ability to define phytoplankton community composition using bulk optical parameters provides a means for initializing the EcoSim model which is now coupled to the ROMs ocean forecast model. Hindcast modeling efforts will assess our skill at providing 3-4 day forecasts for optical properties during the next 2 years.

IMPACT/APPLICATIONS

An integrated system for predicting the 3-dimensional structure of coastal currents, water density and in-water optical properties on the time scales of days is essential to numerous naval operations such as mine counter measures, special forces operations, amphibious landings, and shallow water anti-submarine warfare. The NEMO satellite is being designed to hyperspectral ocean color data for mapping in-water constituents in areas of high naval interest and the derived algorithms from HyCODE will be key to the satellites development. Finally hydrodynamic/optical forecasting system provides the key to integrate and forecast the observed optical properties over time. Finally HyCODE was played a central role to developing optical REMUS AUV and Webb Glider capability. All these observation and modeling systems are relocatable and will be key for future naval operations. Finally development of such a forecasting systems for predictive optics will also be a key civilian deliverable for coastal water quality management.

TRANSITIONS

The data is being freely shared. Data will be disseminated to the ONR WOOD database. Data that is just being finished processed will burned to data CD's (summer 2000 and 2001) and then shipped to the WOOD system in October. Additionally, data will available via Rutgers Ocean Data Access Network (RODAN). The optical data is currently being utilized by NRL and NASA remote sensing projects. Finally the ongoing real-time data, for which the HyCODE program was central to for development, continues to be accessed via the web (over 50,000 hits/day) by the general public, Naval METOC groups, and the U.S. Coast Guard.

RELATED PROJECTS

There were over 27 major institutional partners during the 2000-2001 experiments a large number supported by the HyCODE program. These efforts also complemented other independent efforts such as 1) validation of NAVAIR's KSS Lidar system, 2) ONR-YIP funded AUV bioluminescence prediction efforts (Moline), 3) ONR-STTR sponsored efforts to develop a "smart" fleet of automated Webb Gliders, 4) SeaSpace Inc. efforts to intercalibrate the international constellation of ocean color satellites, 5) calibration and refinement of a suite of NRL-derived satellite algorithms, 6) calibration of atmospheric parameters with NASA's atmospheric Chesapeake Lighthouse and Aircraft Measurements for Satellites experiment, 7) field infrastructure for NASA's YIP and PECASE remote sensing projects (Moline), and 8) model development for ONR's CBLAST Program.

PUBLICATIONS

Schofield, O., Gryzmski, J., Bissett, P., Kirkpatrick, G., Millie, D. F., Moline, M. A. Roesler, C. 1999. Optical monitoring and forecasting systems for harmful algal blooms: Possibility or pipedream? Journal of Phycology. 35: 125-145.

Kirkpatrick, G., Millie, D. F., Moline, M. A., Schofield, O. 2000. Absorption-based discrimination of phytoplankton species in naturally mixed populations. Limnology and Oceanography 42: 467-471.

Bissett, P., Schofield, O., Mobley, C. Crowley, M. F., Moline, M. A. 2001. Optical remote sensing techniques in biological oceanography. In: Methods in Marine Microbiology. Paul, J. (ed). Academic Press, London. 30: 519-538.

Moline, O., Schofield, O., Gryzmski, J. 2001. Impact of dynamic light and nutrient environments on phytoplankton communities in the coastal ocean. In: Modeling Dynamic Systems: Dynamic Modeling for Marine Conservation Ecological Understanding. Lindholm, J. and Ruth, M. (eds) Springer Verlag (In press).

Schofield, O., Bergmann, T., Bissett, W. P., Grassle, F., Haidvogel, D., Kohut, J., Moline, M., Glenn, S. Linking regional coastal observatories to provide the foundation for a national ocean observation network. Journal of Oceanic Engineering. (In Press).

Moline, M. A., E. Heine, J. Case, C. Herren and Schofield O. 2001. Spatial and temporal variability of bioluminescence potential in coastal regions. In: (J. F. Case, P. J. Herring, S. H. D. Haddock, L. J. Kricka and P. E. Stanley eds.) Bioluminescence and Chemiluminescence 2000. World Scientific Publishing Company, Singapore, (In Press).

Moline, M.A., Arnone, R., Bergmann, T., Glenn, S., Oliver, M., Orrico, C., Schofield, O., Tozzi, S. Variability in spectral backscatter estimated from satellites and its relation to in situ measurements in optically complex coastal waters. Journal of International Remote Sensing. (In Press)

Tozzi, S., Schofield, O., Bergmann, T., Moline, M. A., Arnone, R. Variability in measured and modeled remote sensing reflectance for coastal waters at LEO-15. Journal of International Remote Sensing. (In Press)